SYSTEMS TECHNOLOGY LABORATORY SERIES **STL-79-002**

(NASA-TM-84788) EVALUATION OF THE IMP-16 MICROPROCESSOR ORBIT DETERMINATION SYSTEM FILTER (NASA) 31 p HC A03/MF A01 CSCL 09B

N82-29026

Unclas

G3/61 28379

EVALUATION OF THE IMP-16 MICROPROCESSOR ORBIT DETERMINATION SYSTEM FILTER

SEPTEMBER 1979

NASA

National Aeronautics and Space Administration

Goddard Space Flight Center

Greenbelt, Maryland 20771

SYSTEMS TECHNOLOGY LABORATORY SERIES **STL-79-002**

EVALUATION OF THE IMP-16 MICROPROCESSOR ORBIT DETERMINATION SYSTEM FILTER

SEPTEMBER 1979

NASA
National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

FOREWORD

The Systems Technology Laboratory (STL) is a computational research facility located at the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA/GSFC). The STL was established in 1978 to conduct research in the area of flight dynamics systems development. The laboratory consists of a VAX-11/780 and a PDP-11/70 computer system, along with an image-processing device and some microprocessors. The operation of the Laboratory is managed by NASA/GSFC (Systems Development and Analysis Branch) and is supported by SYSTEX, Inc., Computer Sciences Corporation, and General Software Corporation.

The main goal of the STL is to investigate all aspects of systems development of flight dynamics systems (software, firmware, and hardware), with the intent of achieving system reliability while reducing total system costs. The flight dynamics systems include the following: (1) attitude determination and control, (2) orbit determination and control, (3) mission analysis, (4) software engineering, and (5) systems engineering. The activities, findings, and recommendations of the STL are recorded in the Systems Technology Laboratory Series, a continuing series of reports that includes this document. A version of this document was also issued as Computer Sciences Corporation document CSC/TM-79/6208.

The primary contributor to this document include

Charles Shenitz (Computer Sciences Corporation)

Other contributors include

Keiji Tasaki (Goddard Space Flight Center)

Single copies of this document can be obtained by writing to

Keiji Tasaki
Code 582.1
NASA/GSFC
Greenbelt, Maryland 20771

ABSTRACT

This document presents the results of the numerical tests performed in evaluating the National Semiconductor Corporation IMP-16 Orbit Determination System. Included herein are descriptions of the tests performed and tabulations of the numerical results. This document has been prepared in partial fulfillment of the requirements of Task 971 of Contract NAS 5-24300.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

Table

SECTION 1 - INTRODUCTION

The IMP-16 Orbit Determination System (ODS) is a software product packaged on a network of two National Semiconductor Corporation IMP-16 microprocessors. The system is capable of performing orbit determination from satellite-to-satellite tracking (SST) data in Applications Technology Satellite (ATS) range and range-rate (ATSR) format. The estimation scheme used is a Kalman filter, a sequential (recursive) estimator.

This document evaluates this IMP-16 software/hardware system. Section 2 provides the numerical results of various component and system tests performed on the application software. Section 3 discusses overall system timing and performance tests.

The system was developed under Task 885. The validation of the filter was carried out during the present Task 971. Although the specific configuration of a Tracking and Data Relay Satellite (TDRS) which is tracking the Solar Maximum Mission (SMM) is used in the ODS as an example, the system has been developed primarily as a demonstration system. This is in accordance with the general aim of the task, which is to demonstrate the feasibility of using microprocessors in orbit determination work.

Components tested included the orbit propagator, the state transition matrix, the covariance propagator, and the observation model. Each component test was either a comparison with a base run or a numerical approximation to an analytical expression (e.g., difference quotient approximation to a partial derivative). Brief descriptions of the mathematics involved in testing each component are provided herein. Details concerning mathematical specifications may be found in Section 3 of Reference 1.

The application program system tests used the following as observations: IMP-16 simulated data (internal test), Goddard Trajectory Determination System (GTDS) simulated data, and real data run through the IMP-16 preprocessor.

SECTION 2 - NUMERICAL EVALUATION OF THE FILTER

This section presents the numerical evaluation of the application program. Section 2.1 discusses the individual component tests; Section 2.2 discusses the system tests.

2.1 COMPONENT TESTS

The individual filter components tested were the orbit propagator, the state transition matrix, the covariance propagator, and the observation model.

2.1.1 Orbit Propagator

The accuracy of the Runge-Kutta orbit propagator within the IMP-16 ODS was checked soon after that component was built. The results were presented in a memorandum (Reference 2) that forms part of the Task 885 file. The basic result was that after 1 revolution of the Solar Maximum Mission (SMM), the root-sum-square (rss) error in position was 91 meters, although the rss error rose as high as 116 meters during the run. The comparison here was made between the IMP results and a run with the GTDS using a 15-by-15 Earth field with Sun and Moon and an integration step of 10 seconds.

2.1.2 State Transition Matrix

The state transition matrix is used in the filter for propagating the covariance matrix. A second-order (in Δt) Taylor series expansion is used to compute the state transition matrix. (See Section 3.2.4 of Reference 1 for a complete mathematical description.)

Each entry of the state transition matrix is a partial derivative of the form

$$\frac{\partial X_i(t_0 + \Delta t)}{\partial X_j(t_0)}$$

A numerical approximation to the (i, j) entry can be made by the difference quotient

$$\frac{\Delta X_{i,pert,j}}{\Delta X_{j,nom}}$$

where

$$\Delta X_{i,pert,j} = X_{i,pert,j}(t_0 + \Delta t) - X_{i,nom}(t_0)$$

$$\Delta X_{j,nom} = X_{j,nom}(t_0 + \Delta t) - X_{j,nom}(t_0)$$

$X_{i,pert,j}(t_0 + \Delta t) = X_i$-component at time $t_0 + \Delta t$ after the X_j-component was initially perturbed

$X_{k,nom}(t) = X_k$-component at time t, with no initial perturbations

The matrix of numerical difference quotient approximations (Figure 2-1) was compared to the state transition matrix computed by the program (Figure 2-2) for a particular epoch and step size (10 seconds). The matrix in Figure 2-3 contains the error of the numerical approximations relative to the computed IMP state transition matrix entries. That is, the (i, j) entry in this matrix is

$$\frac{NUM(i,j) - \varphi(i,j)}{\varphi(i,j)}$$

where $\varphi(i,j) = (i,j)$ entry in the computed state transition matrix

$NUM(i,j) =$ numerical approximation to $\varphi(i,j)$

2.1.3 Covariance Propagator

The state error covariance matrix is propagated between filter updates. In the absence of state noise the propagation equation, which can be derived from the dynamics model equation, is as follows:

$$\bar{P} = \varphi \hat{P} \varphi^T$$

$$
\varphi_N = \begin{pmatrix}
1.0000\,333 & 8.333\text{ E-5} & 5.00\text{ E-5} & 10.00 & 0.0 & 0.0 \\
6.6667\text{ E-5} & 1.00005 & \text{[illegible]}.00\text{ E-5} & 0.0 & 10.00 & 0.0 \\
3.3333\text{ E-5} & 5.000\text{ E-5} & 1.0000 & 0.0 & 0.0 & 9.99 \\
2.3333\text{ E-7} & 1.50667\text{ E-5} & 7.900\text{ E-6} & 0.99998 & 7.0\text{ E-5} & 4.0\text{ E-5} \\
1.505\text{ E-5} & 6.1\text{[illegible]}\text{ E-6} & 9.750\text{ E-6} & 8.00\text{ E-5} & 1.00006 & 5.0\text{ E-5} \\
7.9167\text{ E-6} & 9.7833\text{ E-6} & -6.950\text{ E-6} & 4.00\text{ E-5} & 5.0\text{ E-5} & 0.99996
\end{pmatrix}
$$

6759/79

Figure 2-1. Approximations to State Transition Matrix Partials

$$
\varphi = \begin{pmatrix}
1.0000019 & 7.5240251\text{ E-5} & 3.9818046\text{ E-5} & 9.9958415 & 0.0 & 0.0 \\
7.5240251\text{ E-5} & 1.0000320 & 4.8589670\text{ E-5} & 0.0 & 9.9958415 & 0.0 \\
3.9818046\text{ E-5} & 4.8589670\text{ E-5} & 9.9996596\text{ E-1} & 0.0 & 0.0 & 9.9958415 \\
3.8587535\text{ E-7} & 1.5054310\text{ E-5} & 7.9669221\text{ E-6} & 1.000019 & 7.524025\text{ E-5} & 3.9818046\text{ E-5} \\
1.5054310\text{ E-5} & 6.4199011\text{ E-6} & 9.7219767\text{ E-6} & 7.5240251\text{ E-5} & 1.0000320 & 4.8584670\text{ E-5} \\
7.9669221\text{ E-6} & 9.7219767\text{ E-6} & -6.8057764\text{ E-6} & 3.9818046\text{ E-5} & 4.8589670\text{ E-5} & 0.99996596
\end{pmatrix}
$$

6759/79

Figure 2-2. State Transition Matrix Computed by Program

$$
\varphi_R = \begin{pmatrix}
3.140\text{ E-5} & 1.075\text{ E-1} & 2.557\text{ E-1} & 4.160\text{ E-4} & 0.0 & 0.0 \\
-1.139\text{ E-1} & 1.800\text{ E-5} & 2.903\text{ E-2} & 0.0 & 4.160\text{ E-4} & 0.0 \\
-1.629\text{ E-1} & 2.903\text{ E-2} & 3.404\text{ E-5} & 0.0 & 0.0 & -5.844\text{ E-4} \\
-3.953\text{ E 1} & 8.230\text{ E-4} & -8.400\text{ E-3} & -3.900\text{ E-5} & -6.965\text{ E-2} & 4.570\text{ E-3} \\
-2.863\text{ E-4} & -4.204\text{ E-2} & 2.883\text{ E-3} & 6.326\text{ E-2} & 2.800\text{ E-5} & 2.903\text{ E-2} \\
-6.304\text{ E-3} & 6.308\text{ E-3} & 2.119\text{ E-2} & 4.570\text{ E-3} & 2.903\text{ E-2} & -5.960\text{ E-6}
\end{pmatrix}
$$

6759/79

Figure 2-3. Relative Error of State Transition Matrix Approximations

where $\bar{P}$ = newly propagated covariance

φ = state transition matrix

$\hat{P}$ = previously updated, propagated, or a priori covariance matrix

To verify that the IMP ODS was propagating the covariance correctly, the following test was performed. A diagonal matrix was entered as the a priori covariance matrix (Figure 2-4). This matrix was then propagated for 1 minute in six steps of 10 seconds each. The propagation was carried out with both the IMP-16 ODS and the Onboard Navigation Package (ONPAC) simulator, a research tool used for premission and real-time studies of onboard orbit determination (Reference 3). The results are shown in Tables 2-1 through 2-3. The differences shown in Table 2-3 are relative differences, computed as follows:

$$\mathrm{Diff}(i,j) = \frac{\mathrm{IMP}(i,j) - \mathrm{ON}(i,j)}{\mathrm{ON}(i,j)}$$

where Diff(i, j) = (i, j) relative error

IMP(i, j) = (i, j) element of the IMP propagated matrix

ON(i, j) = (i, j) element of the ONPAC propagated matrix

The largest relative error appearing in Table 2-3 is -2.62 percent for the σ^2_{xz} term. Most of the errors were considerably smaller.

2.1.4 Observation Model

Tests were made to verify the accuracy of the observation model. The SST range and range-rate measurements modeled by the IMP-16 ODS were compared to measurements simulated by the GTDS. The first four comparisons were reported in a task memorandum (Reference 2). Those results are reprinted here in Table 2-4.

ORIGINAL PAGE IS
OF POOR QUALITY

$$\begin{pmatrix} 0.025 & & & & & 0 \\ & 0.025 & & & & \\ & & 0.0125 & & & \\ & & & 0.25\text{ E-4} & & \\ & & & & 0.25\text{ E-4} & \\ 0 & & & & & 0.125\text{ E-4} \end{pmatrix}$$

6769/73

Figure 2-4. Diagonal A Priori Covariance Matrix

Table 2-1. ONPAC Covariance Propagation Results (1 Minute)

X (km^2)	Y (km^2)	Z (km^2)	$\dot{X}$ (km^2/sec^2)	$\dot{Y}$ (km^2/sec^2)	$\dot{Z}$ (km^2/sec^2)
0.11491 0	−0.26[illegible]17 E-3	0.70631 E-4	0.14977 E-2	−0.70100 E-5	0.22941 E-5
	0.11[illegible]27 0	−0.13270 E-3	−0.70110 E-5	0.15068 E-2	−0.42038 E-5
		0.57413 E-1	0.14741 E-5	−0.27092 E-5	0.74778 E-3
			0.24961 E-4	−0.12447 E-6	0.33858 E-7
				0.25119 E-4	−0.61434 E-7
					0.12461 E-4

6769/73

Table 2-2. IMP ODS Covariance Propagation Results (1 Minute)

X (km^2)	Y (km^2)	Z (km^2)	$\dot{X}$ (km^2/sec^2)	$\dot{Y}$ (km^2/sec^2)	$\dot{Z}$ (km^2/sec^2)
0.11489 0	−0.26435 E-3	0.68777 E-4	0.14976 E-2	−0.69509 E-5	0.22590 E-5
	0.11526 0	−0.13034 E-3	−0.69518 E-5	0.15067 E-2	−0.41770 E-5
		0.57407 E-1	0.14442 E-5	−0.26781 E-5	0.74772 E-3
			0.24960 E-4	−0.12397 E-6	0.33414 E-7
				0.25120 E-4	−0.61194 E-7
					0.12461 E-4

6769/79

Table 2-3. Errors of IMP Covariance Propagation Relative to ONPAC Propagation

X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
−0.174 E-3	−0.179 E-1	−0.262 E-1	−0.668 E-4	−0.843 E-2	−0.153 E-1
	−0.868 E-4	−0.178 E-1	−0.844 E-2	−0.664 E-4	−0.638 E-2
		−0.105 E-3	−0.203 E-1	−0.116 E-1	−0.802 E-4
			−0.401 E-4	−0.402 E-2	−0.131 E-1
				0.398 E-4	−0.391 E-2
					0.0

6769/79

Table 2-4. Observation Modeling

TIME (HMMSS) (OCTOBER 15, 1979)	RANGE (KILOMETERS)/RANGE RATE (CYCLES PER SECOND)				
	ORIGINAL	IMP MODEL	IMP ERROR	FORTRAN MODEL	FORTRAN ERROR
12000	72181.1323/ 6598.80435	72180.121 —	1.011 —	72180.8463 —	0.2860 —
12010	72173.2425/ 5973.84414	72172.319/ 5968.4654	0.923/ 5.379	72172.9876/ 5974.07284	0.2549/ 0.22870
12020	72166.1877/ 5347.96519	72165.271/ 5355.4577	0.916/ 7.492	72165.9643/ 5347.69404	0.2234/ 0.27115
12030	72159.9687/ 4721.27864	72159.065/ 4726.5946	0.903/ 5.316	72159.7761/ 4721.99304	0.1926/ 0.71440

6769/79

NOTES: 1. THE FIRST RANGE RATE CANNOT BE MODELED; A PREVIOUS MEASUREMENT IS NEEDED (NONDESTRUCT MODE).

2. THE ERRORS ARE ABSOLUTE VALUES.

This testing was carried further. The graph of the range residuals (GTDS simulated range minus the range modeled by the IMP ODS) is shown in Figure 2-5. The residuals were computed for each observation (one every 10 seconds) for the first 3 minutes and for sampled times thereafter. The resulting error curve shows that there is some mismodeling either in the IMP observation model or in the GTDS data simulator. This is due to the large residual at the beginning of pass and to the presence of the monotonic decrease in the error with propagation only (i.e., no filtering was done). There was a propagation of 20 minutes (spacecraft simulated time) prior to the first observation. However, a later test starting at the first observation showed little variation in the described results for the first few residuals.

Further testing of the IMP ODS resolved the differences between the IMP model and the FORTRAN test model, but close scrutiny of the R&D GTDS simulated data model revealed an error there. The R&D GTDS simulated observation was modeled over an interval beginning 3/8 of a second later than the corresponding interval for the IMP model. The time displacement of the start in the R&D GTDS model was erroneous. This happened when the correct first estimate of the observation was decreased by multiples of .125 second to yield what is called the ambiguous observation. For the configuration of relay and target satellites considered here, three multiples of .125 second are substracted from the range estimate internally. This ambiguous range is then used for calculating the modeling start time, thus accounting for the 3/8 second time error. This time discrepancy accounts for most of the difference (in either time or distance) between the final modeled ranges. The final difference is proportional to the current average range rate (i.e., average time-rate of change of the range measurement). The correction of this error in the R&D GTDS model will be included in the next update. A corrected version is not available at this time for testing.

Runs were made in which difference quotient approximations to the range and range-rate partial derivatives with respect to the SMM (target satellite) state were taken. The numerical approximations were made as follows:

$$\frac{\partial R}{\partial X_i} \doteq \frac{\text{change in range}}{\text{change in } X_i\text{-component}}$$

$$\frac{\partial R_r}{\partial X_i} \doteq \frac{\text{change in range rate (over the two observations after perturbations)}}{\text{change in } X_i\text{-component}}$$

The results are shown in Table 2-5. Only a rough approximation of the partial derivatives was expected to be obtained by these tests, because the difference quotients were formed from quantities whose changes were measured over 10-second intervals.

2.2 SYSTEM TESTS

Three system tests of the application software were performed. The first used IMP-16 simulated range sum and range-sum-rate data as observations; the second used GTDS simulated data; and the third used real preprocessed tracking data.

2.2.1 IMP-16 Simulated Data

The IMP-16 ODS Kalman filter was unit tested by checking its various component functions, as described in the previous sections. After the succesful completion of these tests, it was possible to run test cases of the entire orbit determination filter process. These test cases, which used observations generated by the IMP-16 ODS observation model, were designed to demonstrate that the filter is working. This internally generated test data was preferred to the GTDS simulated tracking data because it presented no errors in the observation model.

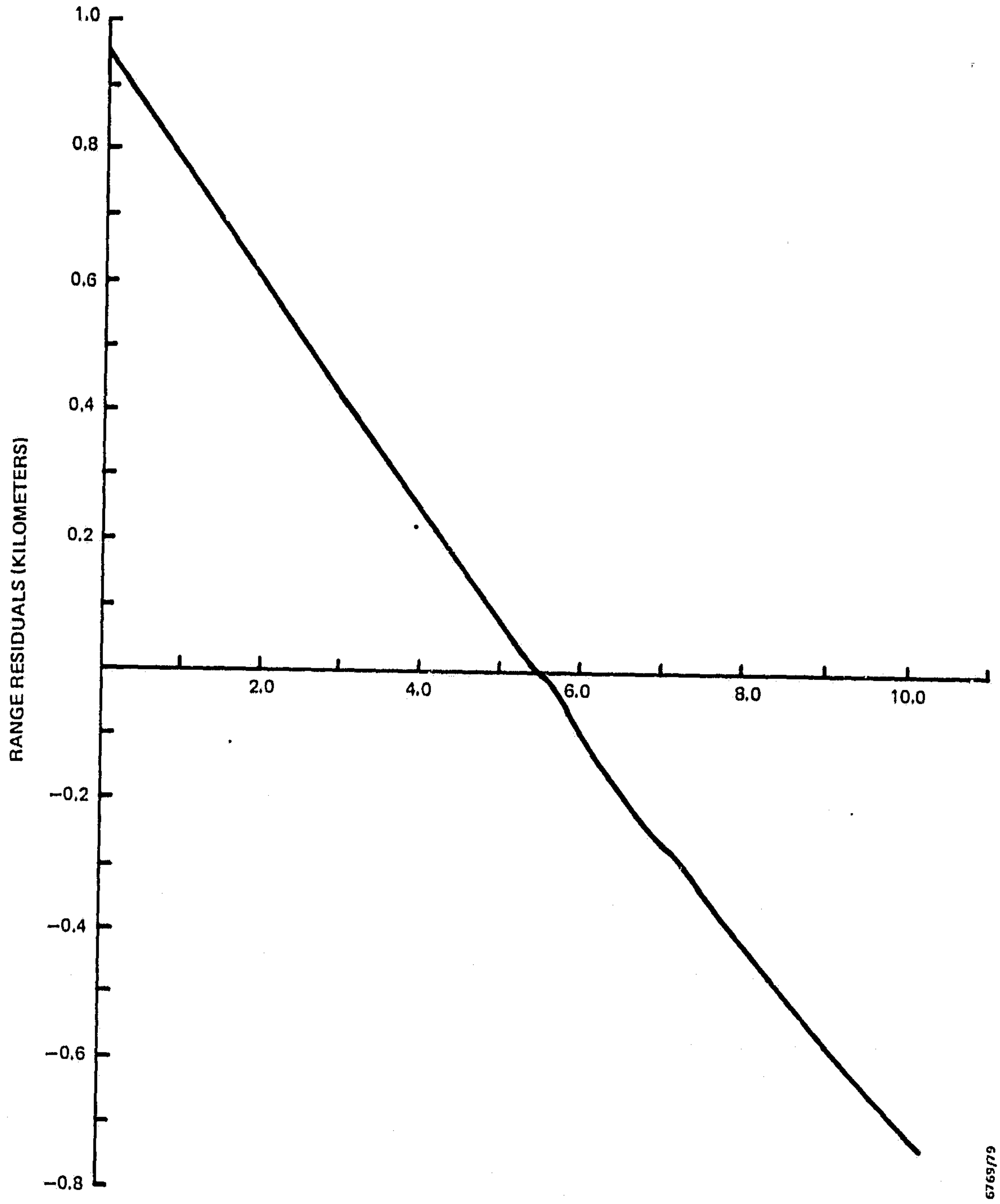

Figure 2-5. Range Residuals (Propagation Without Filtering)

ORIGINAL PAGE IS
OF POOR QUALITY

Table 2-5. Numerical Approximations of Observation Partial Derivatives for October 15, 1979

VARIATION	NUMERICAL APPROXIMATION	PARTIAL MODELED BY IMP
RANGE (1 HOUR, 20 MINUTES, 0 SECONDS)		
$\delta_X = 1$ km	−0.657	−0.6559
$\delta_Y = 1$ km	0.750	0.7507
$\delta_Z = 1$ km	−0.079	−0.0789
$\delta_{\dot{X}} = 0.01$ km/sec	−0.300	0.0
$\delta_{\dot{Y}} = 0.01$ km/sec	0.100	0.0
$\delta_{\dot{Z}} = 0.01$ km/sec	0.0	0.0
RANGE RATE (1 HOUR, 20 MINUTES, 10 SECONDS)		
$\delta_X = 0.1$ km	−0.495	−0.5658
$\delta_{\dot{X}} = 0.01$ km/sec	4893.05	4920.18

6769/79

The method of testing the filter with internally generated test data is as follows. The initial state of the target satellite (SMM) used in generating the test data is perturbed relative to its components by certain quantities. The filter is then started with this perturbed target state and with the original starting state of the relay satellite (TDRS) used for the data generation. The filter attempts to correct the target state based on the internally generated observations. The original (unperturbed) orbit of the target satellite used during the data generation serves as the reference orbit for the target satellite (i.e., for determining the position and velocity errors).

All test cases whose results are specified in this section used the same parameters for filtering, these parameters are shown in Table 2-6. The initial (unperturbed) target satellite states are specified in Table 2-7. This test setup was repeated using both range and range rate (Run A), range only (Run B), and range rate only (Run C) to correct the initially perturbed target element set. The results of these three runs are presented in Tables 2-8 and 2-9, 2-10 and 2-11, and 2-12 and 2-13, respectively.

This set of initial target satellite state perturbations is particularly difficult for the filter to handle. The first range observation residual is very small (8 meters) compared to the rss error of the initial position perturbations (1732 meters). Thus, the input to the filter (i.e., error signal) does not indicate a large deviation from the expected state. Therefore, the state correction process is deferred until one or two observations later. It should be noted that for all test cases run with the given SMM and TDRS orbits, the tracking geometry (observability) is poor. This is confirmed by the very large (almost 1.0) correlations between X and Y and between $\dot{X}$ and $\dot{Y}$. Such poor observability makes the filtering process very difficult and unstable.

Table 2-6. Filter Test Parameters (Internally Generated Data)

COMPONENT	INITIAL STATE PERTURBATION	INITIAL STATE COVARIANCE	PROCESS NOISE COVARIANCE
X	1.0 km	2 km^2	1 E-6 km^2
Y	1.0 km	2 km^2	1 E-6 km^2
Z	1.0 km	2 km^2	1 E-6 km^2
$\dot{X}$	0.5 m/sec	1 E-6 km^2/sec^2	1 E-12 km^2/sec^2
$\dot{Y}$	0.5 m/sec	1 E-6 km^2/sec^2	1 E-12 km^2/sec^2
$\dot{Z}$	0.5 m/sec	1 E-6 km^2/sec^2	1 E-12 km^2/sec^2

6768/79

NOTE:

RANGE VARIANCE: 1 E-8 KILOMETER SQUARED
RANGE-RATE VARIANCE: 8 (CYCLES PER SECOND) SQUARED
DATA RATE (RANGE AND RANGE-RATE PAIR): ONCE EVERY 10 SECONDS UP TO 6 MINUTES AND ONCE EVERY MINUTE AFTER 6 MINUTES
EDITING CRITERION: 48σ

Table 2-7. Initial (Unperturbed) Satellite States (at 1 Hour, 20 Minutes, 00 Seconds on October 15, 1979)

COMPONENT	SMM	TDRS
X	2978.65815 km	26306.1677 km
Y	−5942.30779 km	−32582.1251 km
Z	1957.87311 km	4797.49754 km
$\dot{X}$	5.46081837 km/sec	2.38132324 km/sec
$\dot{Y}$	3.90774318 km/sec	1.94213659 km/sec
$\dot{Z}$	3.53571477 km/sec	0.133964630 km/sec

6769/79

Table 2-8. Filter Test Results for Run A (Range and Range Rate)

MINUTE	POSITION ERROR (m)				VELOCITY ERROR (m/sec)			
	X	Y	Z	POSITION rss	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	VELOCITY rss
0	1005	994	1001	1732	0.5	0.5	0.5	0.866
1	1324	1210	558	1878	0.615	0.270	0.509	0.843
2	1326	1194	562	1871	0.528	0.176	0.471	0.729
3	1347	1218	804	1986	0.419	0.073	0.383	0.572
4	1295	1137	655	1844	0.371	0.015	0.374	0.527
5	922	800	272	1251	0.311	0.127	0.321	0.465
6	790	667	185	1050	0.308	0.084	0.322	0.453
7	534	466	42	710	0.255	0.180	0.251	0.401
8	412	348	−11	539	0.232	0.129	0.204	0.335
9	304	274	−64	414	0.106	0.077	0.087	0.157
10	229	205	−117	329	−0.004	−0.011	−0.020	0.023
11	179	140	−163	280	−0.090	−0.101	−0.005	0.135
12	162	145	−183	284	−0.185	−0.145	−0.032	0.237
13	136	97	−204	264	−0.210	−0.189	−0.014	0.283
14	123	126	−210	274	−0.288	−0.206	−0.035	0.356
15	101	79	−218	253	−0.286	−0.225	−0.007	0.364
16	93	118	−199	249	−0.282	−0.195	−0.011	0.343
17	80	75	−193	222	−0.249	−0.192	0.021	0.315
18	61	109	−191	228	−0.289	−0.198	0.006	0.350
19	57	70	−170	192	−0.227	−0.174	0.040	0.289
20	53	29	−158	169	−0.197	−0.164	0.069	0.265

Table 2-9. State Error Covariance and Correlations for Run A

MINUTE	POSITION VARIANCE/CORRELATION (km^2)				VELOCITY VARIANCE/CORRELATION (km^2/sec^2)			
	σ_X^2	σ_Y^2	σ_Z^2	ρ_{XY}	$\sigma_{\dot{X}}^2$	$\sigma_{\dot{Y}}^2$	$\sigma_{\dot{Z}}^2$	$\rho_{\dot{X}\dot{Y}}$
5	0.5446	0.3856	0.2060	0.9989	6.218 E-7	4.525 E-7	9.367 E-7	0.9413
10	0.1548	8.285 E-2	0.2049	0.9989	6.235 E-7	3.449 E-7	6.993 E-7	0.9919
15	0.1595	7.569 E-2	0.3635	0.9996	2.328 E-7	1.129 E-7	4.010 E-7	0.9895
20	0.1588	6.876 E-2	0.5335	0.9997	7.079 E-8	3.777 E-8	1.579 E-7	0.9762

Table 2-10. Filter Test Results for Run B (Range Only)

MINUTE	POSITION ERROR (m)				VELOCITY ERROR (m/sec)			
	X	Y	Z	POSITION rss	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	VELOCITY rss
0	1005	994	1001	1732	0.600	0.600	0.600	0.866
1	1686	1405	236	2132	0.623	0.301	0.667	0.888
2	1419	1272	557	1985	0.520	0.159	0.484	0.728
3	1447	1336	922	2175	0.403	0.016	0.386	0.558
4	1336	1170	652	1892	0.355	−0.032	0.374	0.517
5	668	666	165	958	0.305	0.178	0.293	0.459
6	696	587	124	919	0.300	0.119	0.300	0.441
7	519	454	33	690	0.234	0.170	0.233	0.371
8	399	336	−31	523	0.178	0.091	0.161	0.257
9	294	264	−107	409	−0.013	−0.012	−0.013	0.022
10	227	200	−173	349	−0.161	−0.129	−0.057	0.214
11	179	137	−223	317	−0.257	−0.226	−0.072	0.350
12	159	141	−240	321	−0.339	−0.257	−0.088	0.434
13	135	94	−244	294	−0.314	−0.264	−0.052	0.414
14	119	122	−247	300	−0.380	−0.271	−0.067	0.472
15	98	76	−242	272	−0.337	−0.262	−0.031	0.428
16	90	115	−214	259	−0.312	−0.215	−0.031	0.380
17	79	74	−197	225	−0.251	−0.193	0.006	0.317
18	60	108	−195	231	−0.290	−0.199	−0.009	0.352
19	55	69	−160	187	−0.215	−0.165	0.029	0.273
20	51	28	−153	164	−0.184	−0.103	0.057	0.218

6769/79

Table 2-11. State Error Covariances and Correlations for Run B

MINUTE	POSITION VARIANCE/CORRELATION (km^2)				VELOCITY VARIANCE/CORRELATION (km^2/sec^2)			
	σ_X^2	σ_Y^2	σ_Z^2	ρ_{XY}	$\sigma_{\dot{X}}^2$	$\sigma_{\dot{Y}}^2$	$\sigma_{\dot{Z}}^2$	$\rho_{\dot{X}\dot{Y}}$
5	0.4454	0.3135	0.1656	0.9989	6.120 E-7	4.340 E-7	9.338 E-7	0.9522
10	0.1434	7.608 E-2	0.1950	0.9991	5.606 E-7	3.080 E-7	6.808 E-7	0.9925
15	0.1577	7.459 E-2	0.3532	0.9998	1.463 E-7	7.063 E-8	3.967 E-7	0.9851
20	0.1573	6.791 E-2	0.5297	0.9399	4.191 E-8	2.461 E-8	1.546 E-7	0.9675

6769/79

ORIGINAL PAGE IS
OF POOR QUALITY

Table 2-12. Filter Test Results for Run C (Range Rate Only)

MINUTE	POSITION ERROR (m)				VELOCITY ERROR (m/sec)			
	X	Y	Z	POSITION rss	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	VELOCITY rss
1	892	2329	891	2648	−0.730	1.806	0.296	1.970
2	2414	1723	2913	4157	−0.062	0.274	0.371	0.465
3	1227	4658	1237	4973	−1.214	−2.822	−0.240	3.081
4	1922	1768	2038	3313	−0.690	−0.683	0.156	0.983
5	3214	1361	3257	4774	−0.439	−0.514	−0.331	0.753
6	284	1287	834	1560	−0.796	−1.177	−0.228	1.439
7	1275	1828	1613	2751	−0.790	−0.407	−0.131	0.898
8	1844	2154	2063	3507	−0.683	−0.301	−0.020	0.747
9	1984	2254	2191	3717	−0.589	−0.717	−0.007	0.928
10	1822	2101	2096	3482	−0.452	−0.922	0.007	1.027
11	1516	1805	1901	3028	−0.316	−0.985	−0.020	1.035
12	1192	1517	1684	2561	−0.268	−0.952	−0.115	0.996
13	870	1172	1461	2065	−0.217	−0.912	−0.202	0.959
14	596	934	1252	1672	−0.286	−0.865	−0.352	0.977
15	349	652	1074	1304	−0.330	−0.846	−0.470	1.023
16	136	483	901	1031	−0.484	−0.844	−0.639	1.164
17	47	270	745	794	−0.587	−0.859	−0.759	1.288
18	−214	159	595	652	−0.798	−0.895	−0.918	1.511
19	−345	−1	471	584	−0.877	−0.924	−1.012	1.627
20	−459	−145	358	600	−0.980	−0.952	−1.097	1.752

6769/79

Table 2-13. State Error Covariances and Correlations for Run C

MINUTE	POSITION VARIANCE/CORRELATION (km^2)				VELOCITY VARIANCE/CORRELATION (km^2/sec^2)			
	σ_X^2	σ_Y^2	σ_Z^2	ρ_{XY}	$\sigma_{\dot{X}}^2$	$\sigma_{\dot{Y}}^2$	$\sigma_{\dot{Z}}^2$	$\rho_{\dot{X}\dot{Y}}$
5	1.541	0.8403	1.383	0.4168	6.430 E-7	5.440 E-7	1.179 E-6	0.8589
10	0.9937	0.5666	0.9017	0.1943	7.719 E-7	5.568 E-7	1.709 E-6	0.8646
15	0.7933	0.3599	0.6228	−8.909 E-2	9.639 E-7	5.078 E-7	2.482 E-6	0.9166
20	0.8475	0.2678	0.6342	−0.1436	1.195 E-6	5.740 E-7	3.352 E-6	0.9502

6769/79

2.2.2 GTDS Simulated Data

Discrepancies between the IMP-16 observation model and the GTDS observation model for SST data have been resolved. Test results will be supplied at a later date when the corrected model is available in R&D GTDS.

2.2.3 Preprocessed Tracking Data

Real preprocessed tracking data will be available upon completion of the tracking data preprocessor during Task 971. The results of filter tests using this data will be released when available.

SECTION 3 - SYSTEM TIMING AND PERFORMANCE

One basic goal of the IMP-16 ODS development project was to determine the ability of the system to keep pace with incoming tracking data in real time. Testing indicates that the computations for modeling and filtering one range and range-rate pair can be performed within 10 seconds (without drag), which is the expected data rate. A comprehensive evaluation must, of course, consider all input/output relevant to a pair of processed observations.

3.1 CURRENT SYSTEM TIMING WITH HEWLETT-PACKARD AND TEXAS INSTRUMENT TERMINALS

The IMP-16 processors used in the prototype orbit determination system discussed here execute input/output under full central processing unit (CPU) control only. Therefore, all input/output activity in a processor requires additional time for that processor. However, the design of the IMP-16 ODS is such that the Data Base IMP (DBIMP) is responsible for input/output with the user, whereas the Computational IMP (COMPIMP) is responsible for the main computational work of the orbit determination process (see the introductions to Chapters 5 and 6 of Reference 1). This division of labor between the two processors is effective under continual processing of points.

Table 3-1 indicates the approximate wall-clock times for the orbit propagator and filter reports for a range and range-rate pair under continual processing. The term "full output" applies to the present form of filter output, which uses one universal format for all output variable (array) types. The term "economized output" refers to new formats to be implemented for filter reports. These new formats will save (printed) space and time. In addition, they will be more organized and, hence, more legible to the user.

From Table 3-1 it may be seen that the IMP-16 ODS can essentially keep pace with real time by using a fast (2400-band or faster) terminal. The Texas Instrument (TI) Silent 700, the terminal for the system, presents an upper physical

Table 3-1. System Speeds

OUTPUT TYPE	HP[1] WALL-CLOCK TIMES (sec)	TI[2] WALL-CLOCK TIMES (sec)
FULL (PRESENT)	12	50
ECONOMIZED (FUTURE)	~10–12	~35

6769/79

[1]HEWLETT-PACKARD 2640A INTELLIGENT TERMINAL AT 2400 BAUD

[2]TEXAS INSTRUMENT SILENT 700 PRINTER TERMINAL AT 300 BAUD (HIGHER AVAILABLE BAUD RATES CANNOT BE USED DUE TO CONCENTRATION OF OUTPUT, LIMITATION OF PRINTING SPEED, AND LIMIT OF TERMINAL BUFFER MEMORY)

limit on system speeds of approximately 3.5 times real time while tracking. Depending upon the length of a data pass (nominally 20 minutes) and the rate at which observations are processed, the system should be able to catch up to real time during data gaps (actual shadowing or imposed gaps). For example, using a 20-second integrator step size and drag, the execution of a propagation through a 76-minute data gap (a 96-minute period minus 20 minutes of tracking data) takes approximately 17 minutes plus the input/output time for periodic printout (plus 1-1/3 minutes for printouts produced once per minute). The approximate wall-clock time for filtering during the 20-minute pass would be approximately 3.5 times 20, or 70 minutes. Thus, the total execution time for computation and input/output during the 96-minute period would be approximately 88 minutes.

3.2 TIMING OF INDIVIDUAL COMPONENTS

The approximate breakdown of the computational time by component function is as follows:

Component Function	Time Required (seconds)
Orbit propagator step without drag	3.3
Orbit propagator step with drag	4.5
Modeling range and range rate with partials	3.0
Filtering range and range rate	4.0

It should be noted that the times indicated in Table 3-1 may increase when the tracking data preprocessor or any other processor (in addition to the COMPIMP) is attached to the DPIMP for active communications.

3.3 CURRENT/FUTURE CORE USAGE

The breakdown of core usage in the IMP ODS is as follows:

Processor	Core (bytes) RAM[1]	Core (bytes) PROM[2]
DBIMP	5.0K	6.0K
COMPIMP	[illegible].6K	15.0K

With the addition of the tracking data preprocessor, core usage is expected to be 11K bytes of RAM and 9K bytes of PROM for DBIMP. COMPIMP core usage will remain the same.

Current memory maps of DBIMP and COMPIMP are provided in Table 3-2.

[1] Random Access Memory (not including base page).

[2] Programmable Read-Only Memory

Table 3-2. Storage Maps

COMPONENT	MEMORY LOCATION[1]	
	RAM	PROM
DBIMP		
EXECUTIVE AND MESSAGE HANDLING SOFTWARE (DBMAIN)	100–64C	8000–8EAB
UTILITIES (PTGTI)	–	8F00–8F7C
TERMINAL OUTPUT (TTYOUT)	13B0–13F6	9000–9459
FLOATING-POINT PACKAGE (SFLPT)	–	94F0–98AC
OBSERVATION FILE (OBSFIL)	660–13A0	–
COMPIMP		
COMPIMP EXECUTIVE AND MESSAGE HANDLER (COMPS)	1280–142F	8000–8220
COMPIMP UTILITIES (UTIL)	–	8230–83FC
FLOATING-POINT PACKAGE (FLPT)	–	8400–87CA
MATH MODELS AND UTILITIES (DAGHST)	180–25D	8800–9170
ORBIT PROPAGATOR (ORBIT)	2B0–726	9190–A7D0
OBSERVATION MODEL (OBS)	800–A24	A800–B109
SEQUENTIAL ESTIMATOR (KALFIL)	2100–23AB	B180–B918
ORBIT DETERMINATION EXECUTIVE (COMP)	1710–1979	BA00–BC8E

[1]ADDRESSES ARE HEXADECIMAL.

REFERENCES

1. Computer Sciences Corporation, CSC/SD-78/6131, System Description of the IMP-16 Microprocessor Orbit Determination Program, C. Shenitz, C. Rabbin, and G. Snyder, October 1978

2. --, Interoffice Correspondence, Task 885 File, Progress of Orbit Determination System, C. Shenitz, July 5, 1978

3. --, CSC/SD-79/6082, Onboard Navigation Package (ONPAC) Simulator User's Guide (Revision 2), J. Dunham, June 1979

STL BIBLIOGRAPHY

Systems Technology Laboratory, STL-78-001, System Description of the IMP-16C Microprocessor Orbit Determination Program, C. Shenitz, C. Rabbin, and G. Snyder, October 1978

--, STL-78-002, Landsat/NAVPAC System Description and User's Guide, S. R. Waligora, December 1978

--, STL-79-001, Intel 8080 Orbit Propagation Program System Description and User's Guide, C. Rabbin, April 1979

--, STL-79-002, Evaluation of the IMP-16 Microprocessor Orbit Determination System Filter, C. Shenitz, September 1979

--, STL-79-003, Multimission Modular Spacecraft Ground Support Software System (MMS/GSSS) MODCOMP Device and MAX IV Dependency Study, T. Weldon and M. McClellan, December 1979

--, STL-80-001, Orbit Determination Software Development for Microprocessor-Based Systems: Evaluation and Recommendations, C. M. Shenitz, July 1980

--, STL-80-002, The Two-Way TDRSS Observation Model for the LSI-11/23 Microcomputer, C. E. Goorevich, July 1980

--, STL-80-003, Automated Orbit Determination System (AODS) Requirements Definition and Analysis, S. R. Waligora, C. E. Goorevich, J. Teles, and R. S. Pajerski, September 1980

--, STL-80-004, Algorithms for Autonomous Star Identification, P. Gambardella, October 1980

--, STL-80-005, Autonomous Onboard Attitude Determination System Specifications and Requirements, M. D. Shuster, S. N. Ray, and L. Gunshol, December 1980

--, STL-81-001, Systems Technology Laboratory (STL) Library Methods and Procedures, W. J. Decker and P. D. Merwarth, September 1981

--, STL-81-002, Mathematical Specifications of the Onboard Navigation Package (ONPAC) Simulator (Revision 1), J. B. Dunham, February 1981

--, STL-81-003, Systems Technology Laboratory (STL) Compendium of Utilities, W. J. Decker, E. J. Smith, W. A. Taylor, P. D. Merwarth and M. E. Stark, July 1981

--, STL-81-004, Automated Orbit Determination System (AODS) Environment Simulator for Prototype Testing (ADEPT) System Description, S. R. Waligora, J. E. Fry, Jr., B. J. Prusiewicz, and G. N. Klitsch, August 1981

--, STL-81-005, Preliminary Automated Orbit Determination System (AODS)/AODS Environment Simulator for Prototype Testing (ADEPT) User's Guide, S. R. Waligora, Y. Ong, J. E. Fry, Jr. and B. J. Prusiewicz, September 1981

--, STL-82-001, GPSPAC/Landsat-D Interface (GLI) System Description, J. B. Dunham, H. M. Sielski, and W. T. Wallace, April 1982

--, STL-82-002, GPSPAC/Landsat-D Interface (GLI) System User's Guide, H. M. Sielski, J. B. Dunham, and P. D. Merwarth, March 1982

--, STL-82-003, Autonomous Attitude Determination System (AADS), Volume 1: System Description, K. A. Saralkar, Y. G. Frenkel, G. N. Klitsch, K. Liu and E. Lefferts, April 1982

--, STL-82-007, System Description for the Global Positioning Subsystem Experiment Package (GPSPAC) Experiment Data Preprocessor (GEDAP), P. D. Merwarth and J. F. Cook, June 1982